

# Dwarf Spheroidal Galaxies in the Virgo Cluster

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Accepted for publication in the *Astrophysical Journal Letters*.

## ABSTRACT

We present a study of the smallest and faintest galaxies found in a very deep photographic R band survey of regions of the Virgo Cluster, totalling over 3 square degrees, made with the UK Schmidt Telescope. The objects we detect have the same physical sizes and surface brightnesses as Local Group dwarf spheroidal galaxies. The luminosity function of these extremely low luminosity galaxies (down to  $M_R \simeq -11$  or about  $5 \times 10^{-5} L_\star$ ) is very steep, with a power law slope  $\alpha \simeq -2$ , as would be expected in many theories of galaxy formation via hierarchical clustering, supporting previous observational evidence at somewhat higher luminosities in other clusters.

*Subject headings:* galaxies: clusters: individual (Virgo) — galaxies: elliptical and lenticular, cD — galaxies: evolution — galaxies: luminosity function, mass function — galaxies: photometry

## 1. Introduction

Recent observations of rich clusters have indicated that the galaxy luminosity function (LF) may turn up at the faint end (e.g., Driver et al. 1994; Mohr et al. 1996; Smith et al. 1997; Wilson et al. 1997; Trentham 1997). From a Schechter (1976) function slope of  $\alpha \simeq -1$ , there appears to be a steepening to  $\alpha \simeq -1.5$  to  $-1.8$  below about  $0.04L_*$  (roughly  $M_R \simeq -18$  or  $M_B \simeq -16.5$  for  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$ ). However the LF is still largely unknown faintwards of  $M_R \simeq -15.5$  ( $M_B \simeq -14$ ), so the overall contribution of dwarf galaxies to the cluster population remains uncertain. The Local Group provides the only well studied sample of such faint galaxies and it appears that below about  $M_R = -15.5$  ( $0.004L_*$ ) the galaxies are virtually all dwarf spheroidals (van den Bergh 1992a). These objects span the magnitude range from about  $M_R \simeq -14.5$  (Fornax) to  $\simeq -8.5$  (Carina), and indicate a rather flat luminosity distribution (van den Bergh 1992b).

In this paper we present a deep photographic survey of significant areas within the Virgo Cluster which span a range of (giant) galaxy densities. The survey, based on digitally stacking UK Schmidt Telescope films (cf. Bland-Hawthorn, Shopbell & Malin 1993), extends the earlier, seminal, survey of Binggeli, Sandage & Tammann (1985), reaching roughly 3 magnitudes beyond their completeness limits. We are able to detect large numbers of faint galaxies, presumably dwarf spheroidals, at magnitudes down to  $M_R \simeq -11$  for an assumed Virgo distance of 18 Mpc (e.g., Jacoby et al. 1992; for consistency we also adopt their value of  $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$  where required).

## 2. The Data and Image Detection

The data used here are part of a larger photographic survey of the Virgo Cluster (Schwartzzenberg, Phillipps & Parker 1995a) using the extremely fine grained, highly efficient Tech Pan films on the 1.2m UK Schmidt Telescope (Phillipps & Parker 1993). Six individual long (1 to 1.5 hour) exposures of the same area, the South East quadrant of the Virgo Cluster, were scanned with the SuperCOSMOS automatic measuring machine at the Royal Observatory Edinburgh (Miller et al. 1992). For convenience, nine separate scan regions 6840 pixels square were created from each film. The pixel scale is 10 microns or  $0.67''$  giving a total area for each scan  $\simeq 1.3^\circ \times 1.3^\circ$ . Two of these scan regions are considered in the present paper, one near the cluster centre, one further out. Note that, while large in itself, the  $\simeq 3.2$  square degrees covered here is only about 1/40 of the full cluster survey area.

The scans from the six separate films were sky subtracted by using a  $256 \times 256$  pixel spatial median filtered version of the data themselves, then matched in intensity by comparing images of a number of calibrating galaxies and median stacked (see Schwartzzenberg, Phillipps & Parker 1996 for details). Median stacking has equivalent noise reduction to simple co-addition and is highly effective in removing artefacts (e.g., due to satellite trails, dust particles adhering to the emulsion and so forth) which affect only one film in the stack. Absolute calibration was via comparison of the images of some brighter galaxies with published CCD photometry (from Gallagher & Hunter 1989), as described by Phillipps & Parker (1993). The final stacked data have an equivalent exposure time of about 7 hours, and the high efficiency of the films, approach-

ing 10% (Parker et al. 1997), results in a pixel-to-pixel sky noise  $\sigma_{sky}$  equivalent to 26.2  $R$  magnitudes per square arc second (henceforth  $R\mu$ ).

Galaxy (and star) images were automatically recovered from the stacked data via a connected pixel algorithm (PISA, Draper 1993), using a detection threshold  $2\sigma_{sky}$  above the sky background, or  $25.45R\mu$ , and a minimum area of 25 pixels (11 square arc seconds). Each image thus has a minimum S/N of 10 and has a magnitude  $R \leq 22$ . (In principle,  $3\sigma$  detection of images of size around  $2''$  would reach a magnitude limit of about  $R = 24$ ). Around 28,000 images are detected in each field and the large minimum area ensures that few are spurious. This was confirmed by comparison of a small area of the photographic data with a CCD image taken on the Anglo-Australian Telescope; 160 of 162 images visible on the film were matched on the CCD frame, including *all* those in the ‘refined’ samples used below.

### 3. Results

The two areas chosen for this study are centred close to M87 and  $3.^\circ 1$  to its south south east, enabling both the cluster core and a more typical cluster region to be investigated. The area immediately around M87 was not searched due to its effectively higher background light level, so the inner and outer surveyed fields cover 1.58 and 1.61 square degrees, respectively. Once the raw catalogues were produced, as above, we ‘refined’ them by requiring that our images met certain criteria aimed at isolating low surface brightness cluster dwarfs. In particular we kept only those images whose isophotal sizes and isophotal magnitudes were consistent with them having exponential profiles (characteristic of virtu-

ally all dwarfs; see Binggeli & Cameron 1991) of scale size  $a \geq 2''$  and central surface brightness  $\mu_0 \geq 22R\mu$  (cf. Figure 1 of Schwartzberg et al. 1995b). This reduced the number of potential Virgo Cluster medium to low surface brightness dwarf galaxy candidates to approximately 17,000 (from 56,000 images of all types). Note that we do not separately remove stars as these should disappear along with the higher surface brightness galaxies. The data set includes galaxies with  $\mu_0$  down to about  $25.2 R\mu$ , but is complete (in the sense that even a  $2''$  scale size gives images exceeding our area limit) only to  $24.5R\mu$ . Further details of other image parameters are given by Schwartzberg (1996), but here we concentrate solely on the magnitudes, though note that we use ‘total’ magnitudes calculated from the measured  $a$  and  $\mu_0$ .

In principle it is possible for an LSBG sample to contain cosmologically dimmed normal surface brightness giants at large redshifts or large non-cluster LSBGs in the background. The former would generally appear much smaller than our detection limit (with  $a \leq 1''$ , cf. Windhorst et al. 1994), while the latter are relatively rare (see Schwartzberg et al. 1995b) and can be subtracted statistically (Turner et al. 1993). Nevertheless, in order to reduce such contamination problems to a minimum, we have again refined our sample to include only the  $\simeq 4000$  objects with  $a \geq 3''$ . These images will also be less affected by seeing; even if the scale lengths are slightly increased by the blurring (and the relatively moderate resolution), the central surface brightness will be decreased to compensate, leading to little error in the derived total magnitudes. In effect we will have merely the LF of galaxies limited at a marginally smaller physical size than would have been the case

in the absence of seeing.

Since we have pre-selected our dwarf LSBG sample in terms of scale size and central surface brightness, we cannot simply subtract standard number counts for the entire population of field galaxies (e.g., Metcalfe et al. 1995) from the magnitude distribution we obtain, in order to arrive at the cluster LF. We have therefore made a subtraction based on the corresponding distribution of *field* LSBGs parameters found by Schwartzberg et al. (1995b). This correction turns out to be quite small compared to our total LSBG numbers (a few percent), so is not critical to our final LF, for the simple reason that most background LSBGs appear much smaller than our cluster LSBG candidates (cf. Karachentsev et al. 1995).

Figures 1a and 1b illustrate the LFs for the outer (895 galaxies) and inner (675 galaxies) cluster regions, respectively. We show here only those galaxies with  $a \geq 3''$  and  $22.0 \leq \mu_0 \leq 24.5R\mu$ , the region of parameter space for which we have a complete and minimally contaminated sample. Note that this is *not* a magnitude limited sample. For instance, we already begin to lose any galaxies with smaller scale sizes at  $M_R \simeq -13$ , whereas our faintest objects have  $M_R \simeq -11$ . Of course, even the loss of small objects at faint  $M_R$  may not be the whole story as far as the LF goes, since there may exist higher surface brightness dwarfs than we are allowing for (perhaps preferentially at bright  $M_R$ ), and we will be missing any even lower surface brightness objects at *all*  $M_R$ . Indeed, recall that we have many candidates for smaller or lower surface brightness galaxies in our original overall sample (see also Schwartzberg 1996).

The LFs plotted for the two regions in Fig-

ure 1 are very similar so an overall LF for the samples can be used. It is clear that the LF is again steep, as in the papers discussed in Section 1, confirming earlier suggestions for Virgo itself by Impey, Bothun & Malin (1988) and Tyson & Scalo (1988). A least squares fit to the combined data gives a power law slope for the range  $15.5 < R < 20.0$  (roughly  $-16$  to  $-11.5$  in  $M_R$ ) of  $\alpha = -2.26 \pm 0.13$ . (Fitting to the individual LFs over the same magnitude range gives  $\alpha = -2.26 \pm 0.14$  and  $-2.18 \pm 0.12$ ). Note that if we restrict attention to the very faint galaxies,  $R > 18$  ( $M_R > -13.5$ ), the steepening is even more dramatic,  $\alpha \simeq -2.5$ . (The turn up appears clearer in the ‘outer’ field, Figure 1a). The amplitudes of the LF for the two separate areas are also similar (in galaxies per magnitude bin per square degree), with the core sample actually having the lower projected density by a factor  $\simeq 0.8$ . LSBGs may be adversely affected by the presence of the giant galaxy M87 in the cluster centre region; Thompson & Gregory (1993) have previously found a similar effect in the core of the Coma Cluster. Note, though, that with the very steep LF slope, a relatively small zero point offset in the calibration between fields, for instance, can have a significant effect on the numbers. For instance an error of  $\Delta m = 0.^m1$  generates a difference of a factor  $10^{0.4(\alpha+1)\Delta m} \simeq 1.12$ . Such errors would make little difference to the shape of the derived LF, since the background contamination is so small. At the bright end, the number of detected LSBGs is in good agreement with that expected from the Binggeli, Sandage & Tammann (1985, 1988) Virgo Cluster LF, given the small numbers of these objects in our samples (see Figure 1b). It is clear that our LF departs from theirs at the expected point where incompleteness and lack of very low surface

brightness objects starts to affect their sample, beyond  $R \simeq 17$ . (We assume here typical early type galaxy colours,  $B - R = 1.5$ , for the dwarf spheroidals; if they actually have bluer colours, as often seen in low surface brightness galaxies, this would slightly improve the match).

#### 4. Conclusions

By co-adding very deep UKST photographic films we have been able to probe the dwarf population of the Virgo Cluster down to  $M_R \simeq -11$  ( $\simeq 5 \times 10^{-5} L_*$ ). The central surface brightness limit for our sample is  $25R\mu$ , corresponding roughly to  $26.5B\mu$  for early type galaxy colours. In both luminosity and surface brightness this is thus one of the deepest surveys yet performed. In particular, our limits allow us to survey well into the regime of the dwarf spheroidal galaxies (Irwin & Hatzidimitriou 1995); the luminosity limit is 25 times fainter than the Fornax dwarf, for instance. We have therefore been able to gather by far the largest sample of dwarf ellipticals/dwarf spheroidals currently known. Of course, in the absence of redshifts, these ‘detections’ are on a statistical basis only. However, given the paucity of LSBs of moderate to large angular size in the general field, we are confident that the large majority of our candidates are genuine cluster dwarfs.

The luminosity function of the dwarfs is very steep, with  $\alpha \simeq -2$ , confirming values found over much more limited magnitude ranges in other clusters (e.g., Smith et al. 1997; Trentham 1997). Bernstein et al. (1995) reached similarly faint levels to those discussed here with very deep CCD imaging of a very small area at the core of the Coma cluster (to  $M_R = -11.4$ ). They found a less steep LF than most other deep surveys,  $\alpha \simeq -1.3$ ,

but the centre of Coma may be a rather special environment. Though their surveys are less deep, Biviano et al. (1995) and Thompson & Gregory (1993) find steeper slopes for parts of Coma further from the centre.

A steep slope,  $\alpha \simeq -2$ , is as expected generally in any hierarchical structure formation model (eg. White & Frenk 1991; Blanchard, Valls-Gabaud & Mamon 1992; Evrard, Summers & Davis 1994; Frenk et al. 1996; Kauffmann Nusser & Steinmetz 1997). Note that since we are observing at long wavelengths ( $R$  band), and in any case we expect most of our objects to be dwarf ellipticals with little or no recent star formation, our LF shape should closely match that of the more fundamental (baryonic) mass function, allowing a simpler comparison with theoretical models. There is a suggestion that the dwarf LSBG to giant galaxy ratio is smaller in the cluster core than further out. Analysis of the whole cluster survey area should allow us to quantify this in more detail (see also Phillipps et al. 1997).

We might, finally, note that much smaller and fainter galaxies can be *detected* in our data than are present in our photometric samples. Indeed, we can reach down to about  $M_R \simeq -8.5$  at the distance of Virgo, the same as the Carina dwarf, the lowest luminosity system currently known. Unfortunately, though, these images are indistinguishable from those of the (very numerous) general background galaxies. However, we should still be able to estimate their numbers through a comparison with an identically observed non-cluster field. This work will be reported in a subsequent paper. At some point we should certainly expect to see a turn over in the LF, since  $\alpha = -2$  is the critical value at which the integrated galaxy light formally diverges.

If the currently found slopes in the range  $-2$  to  $-2.5$  were to continue down to, say,  $M_R = -8$ , then the dwarf galaxies fainter than  $M_R = 16$  would contain approximately 0.1 to 1.0 times as much light as the brighter galaxies. For a constant  $M/L$  (or perhaps more reasonably, a fixed *baryonic*  $M/L$ ) this would obviously increase the total mass in cluster galaxies by a factor between 1.1 and 2.

We would like to thank the UK Schmidt Telescope for the provision of the usual excellent photographic material and the SuperCOSMOS group at ROE for scanning them. SP and JBJ thank the Royal Society and the UK PPARC, respectively, for financial support.

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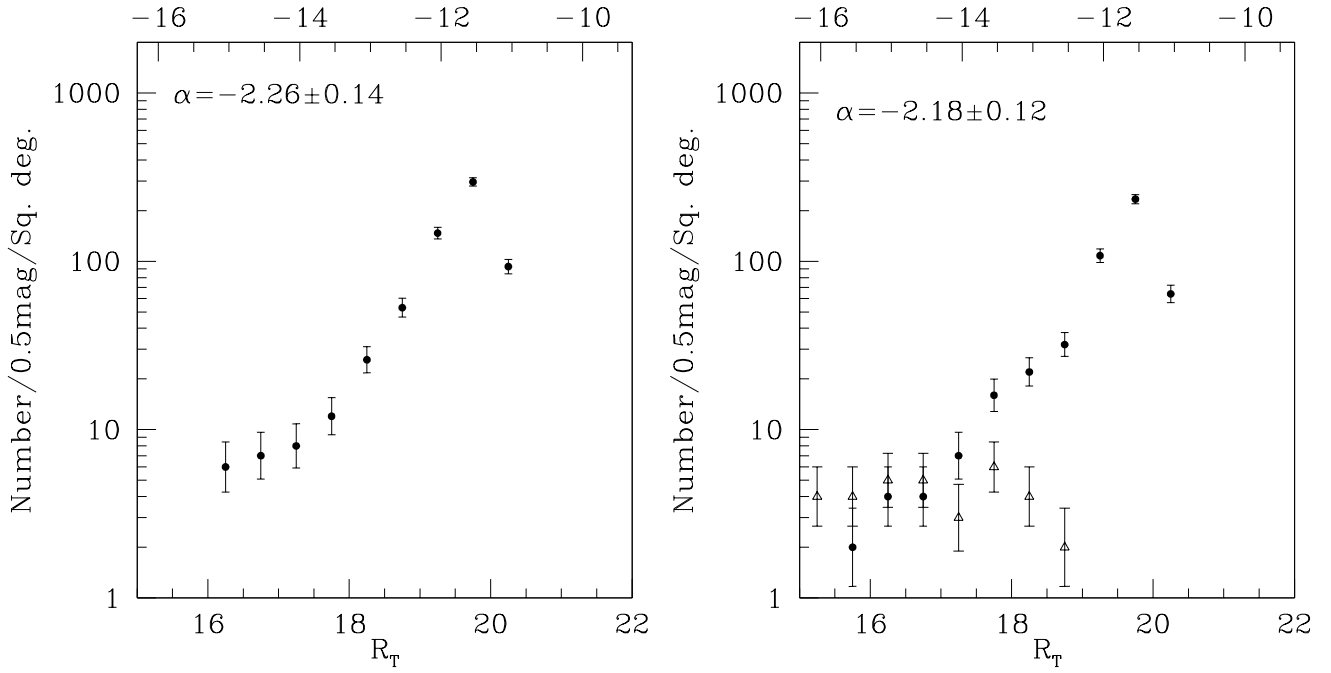


Fig. 1.— The absolute magnitude distribution of Virgo LSBGs (as defined in the text), for the (a) outer and (b) inner area samples. Error bars shown are based on Poissonian statistics. The luminosity function of Sandage et al. (1985) is also shown (open triangles) for the Virgo Cluster Catalog galaxies which overlap with the inner field. (We assume for this comparison  $B - R = 1.5$ .)